APPENDIX B - THE PROCESS OF DEVELOPING LIQUEFACTION HAZARD MAPS

The Key Issue – Quantifying How Hard the Ground Must Shake to Trigger Liquefaction

A key component of mapping liquefaction hazard is estimating, in map form, the shaking needed to trigger liquefaction. The answer is based, in part, on just how susceptible the material is to liquefaction. Thus, in areas exposed to moderate shaking, a material that is highly susceptible to liquefaction may liquefy, but an adjacent material that is moderately susceptible may not. The tricky part is to quantify this relationship so that it can be used to develop maps estimating liquefaction hazard. The principal difficulty in quantification is that the process is based on making assumptions needed to convert general mapped units with variable properties to discrete units with specific properties.

Early Efforts Using Distance from Earthquake Source

In the 1970s and 1980s, shaking effects were estimated by relating earthquake magnitude to maximum distance from the earthquake source (or fault) for liquefaction effects. One formula, developed by Youd and Perkins (1978), relates distance to surface-wave magnitude as: $\mathbf{M = 5 + 1.15 \log d}$, where $\mathbf{M}$ = earthquake magnitude that will trigger liquefaction and $\mathbf{d}$ = distance from the fault source of the earthquake. In a later effort, Keefer (1984) plotted magnitude versus the maximum distance from the fault rupture zone to various types of earthquake-triggered ground failures (including lateral spreads and flows).

The problem with these early approaches is that, in the Bay Area, most artificial fills that are highly susceptible to liquefaction are on Bay mud, a material that significantly amplifies and lengthens shaking. These early approaches ignore variations in shaking amplification attributable to geologic materials. See Perkins and Boatwright (1995) for more information on the role of geologic materials in shaking amplification.

Efforts Correlating Triggering Shaking with Intensity

Other efforts to estimate levels of ground shaking needed to trigger liquefaction have used shaking intensity, a measure of the effect of an earthquake at a specific location. Most intensity maps use the modified Mercalli intensity scale to define shaking level in terms of damage. See the third column of Figure 1 in the main report for a summary description. See Richter (1958) for a more detailed description and definition of modified Mercalli intensity.

Richter (1958) includes liquefaction-related descriptions in his definitions for higher modified Mercalli intensities:
MMI VII – "small slides and caving in along sand or gravel banks"
MMI VIII – "cracks in wet ground"
MMI IX – "in alluvial areas sand and mud ejected,… sand craters"
MMI X – "sand and mud shifted horizontally on beaches and flat land"

Keefer (1984) notes that the "predominant minimum intensity" for lateral spreads and flows in his analysis was MMI VII.

The problem with using these types of intensity descriptions to estimate shaking levels needed to trigger liquefaction is that the information is not quantitative, and thus of minimal usefulness in modeling hazards in future earthquakes. To solve this problem, some efforts at combining shaking hazard with liquefaction susceptibility to create liquefaction hazard have used estimates of earthquake accelerations.

Use of Arias Intensity to Estimate Shaking Levels Needed to Trigger Liquefaction

Other research has been conducted using Arias intensity[1], an estimate of the energy delivered to structures on the earth's surface (see, for example, Kayen and Mitchell, 1997). From our perspective, using Arias intensity has an inherent advantage – the values (expressed in meters per second) can be directly correlated with various measures of shaking velocity. Because ABAG's shaking intensity maps also are based on average shaking velocity, rather than acceleration, this Arias intensity research allows us to make full use of ABAG's ground shaking maps. [See Perkins and Boatwright, (1995) and Perkins (1998) for information on these shaking hazard maps.]

To use Kayen and Mitchell (1997) work correlating liquefaction with Arias intensity, ABAG's maps of modified Mercalli intensity need to be correlated first with standard 1-component Arias intensity, and then to the 2-component Arias intensity at depth plotted by Kayen and Mitchell. These conversions are supplied in Table B1, below.

TABLE B1: Approximate Relationships Among Intensity Scales[2]

NOTE – These correlations apply to the ABAG maps because of the way the maps were generated. ***They do not work with other MMI maps.*** Therefore, this table should not be used to convert MMI maps generated by others to Arias intensity. ***All of the quantitative measurements of shaking strength used in this table have units of velocity, not acceleration.***

Modified Mercalli Intensity (as shown on ABAG maps)	Undamped Velocity Response Spectra (cm/sec)	Peak Velocity (cm/sec)	1-component Arias Intensity (m/sec)	2-component Arias Intensity (m/sec)	Approximate 2-component Arias Intensity at Depth (m/sec)
XII	(more than shaking)				
XI	(more than shaking)				
X	450	286	48.7	97.4	78
	300	191	21.6	43.2	35
IX	204	130	10.0	20.0	16
	141	90	4.8	9.7	7.8
VIII	96	61	2.2	4.3	3.5
	66	42	1.1	2.2	1.8
VII	45	30	0.5	1.0	0.8
	30	19	0.2	0.4	0.3
VI	21	13	0.1	0.2	0.16
	15	10	0.05	0.1	0.08
V	9	6	0.02	0.04	0.03

[1] Arias intensity is an estimate of the energy delivered to structures on the earth's surface. The actual formula is provided in Arias (1970):

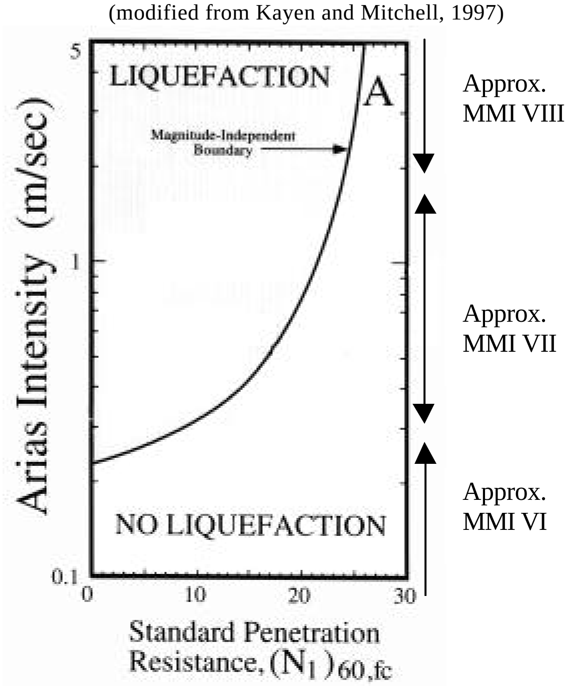
$$I_a = \frac{p}{2g}\int_0^{\infty}[a(t)]^2\,dt)$$

where I_a is Arias intensity, g is the acceleration due to gravity, and the remaining term is the integral of the square of acceleration over time.

[2] Kayen and Mitchell relate liquefaction to 2-component Arias intensity at depth – a variable removed for this simplified analysis by assuming most liquefaction will occur at approximately 5 m below the surface. The categories used on ABAG's MMI maps were converted to equivalent 1-component Arias intensity by J. Boatwright (personal comm., 1998). The 1-component Arias intensity values in Table B1 are the average of the two horizontal components, not the maximum of the two. Thus, the 2-component values are simply double the 1-component value. Finally, the Arias intensity at 5 meters is roughly 80% of the surface intensity for earthquakes of approximately moment magnitude = 7 (Kayen, and Mitchell, 1998, Kayen, personal comm., 2001).

FIGURE B1 – ESTIMATED TRIGGERING INTENSITY FOR LIQUEFACTION USING PENETRATION RESISTANCE DATA

(modified from Kayen and Mitchell, 1997)



The second conversion needed to use the Kayen and Mitchell (1997) work is between general liquefaction susceptibility categories mapped by Knudsen and others (2000) and the engineering property of soil materials used by Kayen and Mitchell – standard penetration test normalized blow counts with a fines content correction for "clean sand" or **SPT** ($\mathbf{N}_{1,fc}$) **60**. No data are generally available to make estimates of the SPT values for the various susceptibility units. Part of the problem is the wide range of SPT values for each Quaternary geologic map unit. For example, fill over Bay mud can have SPT values ranging from 3 for non-engineered fill to over 35 for engineered fill. The other problem is that SPT data collected for individual development projects typically are not available for use in research. CDMG is beginning to collect SPT and other engineering data as part of their Seismic Hazard Mapping Program (Knudsen, personal comm., 2001).

Use of Pipeline Damage Statistics from the Loma Prieta Earthquake to Estimate Shaking Levels Needed to Trigger Liquefaction

Because of this lack of quantitative SPT information, we examined pipeline damage statistics from the Loma Prieta earthquake. The principal problem with the pipeline data is that there is no information for liquefaction effects in MMI IX and MMI X. In addition, not all of the pipeline leaks are related to liquefaction. However, these data show a clear increase in pipeline leaks per km of exposed pipeline above MMI VII for areas of very high liquefaction susceptibility. The triggering intensity for significant pipeline leaks in areas of high and moderate susceptibility appears to be MMI VIII. Interestingly, the statistics show that areas of high susceptibility in MMI VII and MMI VIII actually experienced fewer leaks/km than areas of moderate susceptibility, indicating the preliminary nature of our liquefaction hazard mapping efforts. See Appendix C for more information.

Estimates of Shaking Levels Needed to Trigger Liquefaction Used to Create Liquefaction Hazard Maps

We made qualitative assignments of the relative liquefaction hazard for various combinations of liquefaction susceptibility and shaking intensity. These assignments were based on a combination of Kayen and Mitchell (1997), Richter (1958), and Keefer (1984), together with the statistical information on pipeline and other damage described in Appendix C. This qualitative assessment is summarized in Figure B2, below.

As shown in Figure B2, we estimated that only some materials mapped as having very high liquefaction susceptibility will liquefy when exposed to strong shaking (modified Mercalli intensity (MMI) VII), while liquefaction of materials mapped as less susceptible will be triggered with very strong shaking (MMI VIII). The imprecise nature of the shaking model and the variability of the Quaternary deposits make liquefaction in areas shaken less than MMI VII, or in areas mapped as having a low to very low liquefaction susceptibility, a statistical possibility, but unlikely. See Technical Appendix C, ABAG's analysis of data on damage from the Loma Prieta earthquake, for additional statistical information.

FIGURE B2 – LIQUEFACTION HAZARD BASED ON COMBINATIONS OF MODIFIED MERCALLI INTENSITY AND LIQUEFACTION SUSCEPTIBILITY MAP UNITS

MMI Value	Description of Shaking Severity	Summary Damage Description Used on 1995 Maps	Liquefaction Susceptibility Category				
			Very Low	Low	Moderate	High	Very High
I							
II							
III							
IV							
V	Light	Pictures Move					
VI	Moderate	Objects Fall					
VII	Strong	Nonstructural Damage			Moderately Low	Moderately Low	Moderate
VIII	Very Strong	Moderate Damage			Moderate	Moderate	Moderate
IX	Violent	Heavy Damage			**High**	**High**	**High**
X	Very Violent	Extreme Damage			**High**	**High**	**High**

Need for Additional Research

There is a need for additional research on the shaking levels needed to trigger liquefaction for the different categories of Quaternary deposits. Such research will improve on the accuracy and reliability of the regional liquefaction hazard mapping.

The maps are only as accurate as the ground shaking, liquefaction susceptibility, and correlation table used to create them.

References –

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